Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES): Capturing Uncertainty in the Common Tactical Environmental Picture

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LONG-TERM GOALS

UNITES is a unique, interdisciplinary team with expertise spanning the environment (physical oceanography and bottom geology), ocean acoustics (propagation, ambient noise, reverberation and signal processing), and tactical sonar systems. The overall goals of the research are to enhance the understanding of the uncertainty in the ocean environment (including the sea bottom), characterize its impact on sonar system performance, and provide the Navy with guidance for understanding sonar system performance in the littoral ocean. The Harvard work is ongoing within the context of this overall program.

OBJECTIVES

The overall objectives of this research are to:

1. define and characterize the variabilities and uncertainties in the components and linkages of the general physical-geo-acoustical-sonar system (the end-to-end System) relevant to the support of naval operations, and

2. quantitatively transfer the spatial-temporal environmental variabilities and uncertainties through the System, including coupled interactions, in order to determine uncertainty measures, sensitivities and feedback needed to improve operational predictions and parameters

Specific objectives of the Harvard effort are to:

1. develop generic methods for efficiently and simply characterizing, parameterizing, and prioritizing the ocean physical variabilities and uncertainties arising from regional scales and processes

2. construct, calibrate and evaluate uncertainty and variability models for the ocean physics and address forward and backward transfer of uncertainties based on the process of end-to-end data assimilation

3. transfer uncertainties from the acoustic environment to the sonar and its signal processing

4. contribute to overall synthesis and provide scientific guidance for the end-to-end problem

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14. ABSTRACT

UNITES is a unique, interdisciplinary team with expertise spanning the environment (physical oceanography and bottom geology), ocean acoustics (propagation, ambient noise, reverberation and signal processing), and tactical sonar systems. The overall goals of the research are to enhance the understanding of the uncertainty in the ocean environment (including the sea bottom), characterize its impact on sonar system performance, and provide the Navy with guidance for understanding sonar system performance in the littoral ocean. The Harvard work is ongoing within the context of this overall program.

15. SUBJECT TERMS

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APPROACH

Our technical approach is based on modeling and simulating physical fields and high order uncertainties for the PRIMER / SHAREM-ACT-ASIAEX regions. Environmental data is assimilated in the Harvard Ocean Prediction System (HOPS) using Error Subspace Statistical Estimation (ESSE) and Optimal Interpolation (OI). 4D Monte-Carlo-based simulations of physical fields, parameters and their respective dominant uncertainties are carried out. The dominant uncertainties (error subspace) are initialized, forecast and reduced via data assimilation. The results are analyzed and the physical estimates transferred to acoustics/signal processing models. Stochastic error models for unresolved processes, forcing and boundary condition errors, and environmental noise, are further developed and improved. Applied mathematics research for representing, characterizing, capturing and reducing (end-to-end) uncertainty for scientific and Naval purposes is carried out. End-to-end data assimilation and adaptive sampling are researched and carried out. A focus is the extension of HOPS/ESSE schemes to coupled physical-geo-acoustical assimilation/sampling schemes. A.R. Robinson is one of the two co-leaders of the UNITES team and is the scientific team leader. P.F.J. Lermusiaux carries out the technical research. The Harvard team also coordinates, provides overview and guides the end-to-end system research.

WORK COMPLETED

A.R. Robinson and P.F.J. Lermusiaux attended the ONR Uncertainty DRI Review and Planning Meeting held at Scripps Institution of Oceanography in June 2001, and presented the tasks completed and the technical accomplishments for FY02. The two presentations, entitled "Transfer of uncertainties through physical-acoustical-sonar end-to-end systems: a conceptual basis" and "Physical-acoustical data assimilation and characterization and transfer of uncertainties to the sonar: Error subspace statistical estimation." are available on the web (see header information and references at the end of this document). Several UNITES team meetings occurred during FY02, including meetings with members of other teams (Seabed Variability and MIT).

We have been working in close collaboration with Philip A. Abbot and his team, and have defined the conceptual basis of an end-to-end system [6], including its components, linkages and feedbacks of uncertainty from the environment to the sonar. Specificities and examples focused on the forward transfer of uncertainties for a Shelfbreak PRIMER end-to-end system. Multiple meetings were held so as to establish a common language and understanding for our respective disciplines. Based on these information exchanges, a comprehensive and schematic picture of the end-to-end system crystallized, being sufficiently complex to identify the various interactions among the different components of the system but remaining simple enough for clear understanding.

In collaboration with Prof. Ching-Sang Chiu, the transfer of ocean physical forecast uncertainty to acoustic prediction uncertainty in the shelfbreak PRIMER environment has been conducted, including histogram estimates of the sound speed and Transmission Loss (TL) uncertainties [2]. Using ESSE, the dominant physical uncertainties were initialized using PRIMER data and HOPS physical models and transferred through the coupled-mode sound propagation NPS model to produce coupled uncertainties for the physical field volume around the PRIMER region and for the acoustic wave field in a vertical plane across the shelfbreak front.

The ESSE physical results were discussed and evaluated in collaboration with WHOI. In particular, physical model outputs were given to Dr. Gawarkiewicz and his team, and several exchanges of data and information occurred between HU and WHOI. This collaboration is ongoing.

Coupled physical-acoustical data assimilation (DA) [1] was carried out for simulated examples [5,7]. These advances entailed extending ESSE assimilation schemes to physical-acoustical fields. Importantly, this is a truly coupled four-dimensional estimation, including both the acoustic and oceanic variables in the state vector. From the computed physical and acoustical uncertainties, a coupled error subspace is defined, capturing the dominant uncertainties in each field and their covariances. The available physical and acoustical data are then assimilated into the predicted fields in accord with the error subspace and all data uncertainties. The criterion for data assimilation is presently to correct the predicted fields such that the total error variance in the error subspace is minimized. The approach was exemplified based on twin-experiments using the physical PRIMER data.

Uncertainties computed via ESSE for the single-frequency forecast TL were processed to obtain an estimate of the TL uncertainties for a broadband sonar system. A variable-width running-range average was applied to the ESSE ensemble of single-frequency TL realizations. This produced an estimate of the uncertainties in the broadband TL term of a passive sonar equation.

Discussions on uncertainty predictability, e.g. [8], and simple rules-of-thumb were carried out with WHOI, OASIS and NPS based on the PRIMER and ASIAEX data sets and simulations. In collaboration with Prof. Miller at OSU, the stochastic modeling of uncertainty, incorporating the Stratonovich calculus has begun. An extensive literature search on uncertainty, predictability, (fuzzy) information theory, imprecise probability theory and Bayesian and maximum entropy methods has been carried out. Both general, applied mathematics and focused, ocean-atmosphere manuscripts and books, have been collected and continue to be studied.

Research on efficient visualization of ESSE uncertainties was continued, in collaboration with Prof. Alex Pang and his group [3]. The improvements of the visualization technique included showing cues on the location of the largest errors and selecting more adequate transfer functions.

Considering algorithms and software developments, e.g. [4], the ESSE scheme for physical-acoustical data assimilation was implemented. The computation of multivariate EOFs and the stochastic error models were improved. Software for the computation and analysis of error Probability Density Functions (PDFs) for interdisciplinary physical-acoustical-sonar fields were developed.

RESULTS

Our main results for FY02 involve research on the end-to-end system concept, the physical-acoustical data assimilation and the transfer of environmental uncertainties to sonar equations.

1. End-to-end system

A conceptual basis of the end-to-end system approach, including its components, was derived and exemplified using shelfbreak-PRIMER data and models. Specifically, a generic approach to: (i) characterize variabilities and uncertainties arising from regional scales and processes, (ii) construct uncertainty models for a generic sonar system, and (iii) transfer uncertainties from the acoustic environment to the sonar and its signal processing, was obtained. Fig. 1 schematizes the end-to-end system from the model point of view, where models are used to represent each of the coupled dynamics (boxes) and also the linkages to observation systems (circles). The diagram illustrates the forward transfer of information, including uncertainties, in terms of observed, processed and model data (dots on arrows) and products and applications (diamond). The system concept encompasses the interactions and transfers of information with feedback from: i) observing systems, the information being physical-acoustical-bottom-noise-meteorological-sonar data, ii) coupled dynamical models, the information being physical-acoustical-bottom-noise-sonar state variables and parameters, and, iii) sonar equation models, the information being parameters in sonar equations.

The data/information dots are enlarged on Fig. 2a; the detailed model and data diagram is on Fig. 2b. In these diagrams, uncertainties are defined by a representation of the likely errors in the estimated fields, usually in some probabilistic sense. Although uncertainties can be reduced, e.g. via data assimilation, there always remain some irreducible errors which need to be represented. There are several methodologies to represent errors and, for such complex interdisciplinary systems, efficient representations are an issue. The ESSE approach focuses on the errors that matter, the error subspace. The components of the end-to-end system are described in [6], based on the PRIMER experiment.

2. Coupled physical-acoustical DA

ESSE was successful in carrying out the estimation of ocean physical and acoustical fields as a single coupled data assimilation problem for a twin experiments based on PRIMER data [5]. Environmental fields and their dominant uncertainties are predicted and transferred to acoustical fields and uncertainties by an acoustic propagation model. This transfer of uncertainties is described in [2]. The resulting coupled dominant uncertainties define the error subspace. The physical and acoustical data are then assimilated such that the total error variance in the error subspace is minimized. Results of a coupled assimilation based on 1996 PRIMER data are illustrated on Figs. 3-4.

As a first step, the coupled assimilation is an "identical twin experiment". The goals are to study the assimilation in a simulated situation and to find out if the *a posteriori* fields become close to the known "true" fields. The physical data are PRIMER profiles of temperature and salinity, but the acoustical data are only model data. They are simulated towed-receiver TL data along path 1, i.e. TL1 (Fig. 3). The TL observations are made at constant 70 m depth, every 50 m from a range of 150 m to almost receiver 1. These are very sub-sampled data since the (r,z) acoustic grid resolution is 5 m by 5 m.

The simulated true TL, *a priori* TL (i.e. the mean or forecast), *a posteriori* TL (after assimilation) and the TL realization closest to the *a posteriori* TL are shown on Fig. 4. Even though the true TL is challenging to retrieve and the sub-sampled data are limited, the *a posteriori* TL is substantially closer to the true TL than the mean TL. From the ESSE ensemble of predicted TLs, one can select for best estimate the TL the closest (in some metric sense, here a RMS measure) to the *a posteriori* TL. This realization is at some locations closer to the true TL than the *a posteriori* TL. Actual data residuals confirm these findings. The ESSE error covariances (not shown) importantly estimate the uncertainty reduction as a result of the coupled data assimilation [5,7].

3. Transfer of environmental uncertainties to the sonar

To transfer the acoustical uncertainties to the broadband sonar system, the ESSE ensemble of single-frequency (224Hz) TL realizations are processed, using a variable-width running-range average. The result is an ensemble of broadband TL estimates, from which uncertainties can be characterized, as shown on Fig. 5.

From this ensemble, the uncertainty associated with the broadband TL term of a sonar equation are directly computed. It is represented on Fig. 6 by the histograms of deviations from the mean broadband TL (i.e., the error PDF estimates) as a function of range and depth. The computed environmental PDFs are found to be depth and range dependent. Near the depth (55 m) of the main wave-guide, the error standard deviation is relatively constant with range and relatively large, around 3 to 4 (db). Closer to the surface (30 m) and closer to the bottom (85 m), standard deviations tend to decrease with range (down to 2 db), leading to a higher PDF peak. Finally, the shape of the PDFs (skewness, kurtosis, double peaks, etc.) are found to be dependent on position with respect to the shelfbreak front.

IMPACT/APPLICATIONS

The end-to end framework is designed to support the individual components, environmental as well as non-environmental uncertainties (system related) so that an assessment of the dominant mechanism of uncertainty as it affects the SNR/SIR (Fig. 1) can be identified. The ability to assess the importance of the individual uncertainty components in the sonar performance prediction along within its aggregate uncertainty can be an invaluable tool in the development of tactical guidance.

Transferring and forecasting uncertainties from the physics, through the acoustics, using ESSE and processing these dominant error estimates to obtain TL uncertainties for a broadband sonar equation is a significant interdisciplinary progress. Coupled four-dimensional data assimilation for physical-acoustical fields has the potential to provide significant advances in physical and acoustical ocean sciences and fleet applications. A specific impact is the four-dimensional reduction of errors in each discipline based on data from all disciplines.

The direct UNTIES-team application is to assist the sonar "prediction community" by providing a probabilistic representation of sonar system performance. Our approach provides a systematic method to incorporate uncertainties due to the environment and to transfer the effects of these uncertainties, in the end-to-end problem through the sonar systems under consideration. The operator can thus use this information to operate the system more effectively and make more informed decisions on search, risk, expenditure of assets (weapons) and assumptions of covertness.

TRANSITIONS

Rules-of-thumb, lessons learned, technical implications for effective environmental sampling strategies for the fleet and other tactical insights are being presented by the UNITES team to appropriate fleet personnel and Navy-ONR working groups or programs, e.g. the ONR Littoral ASW FNC program and the Advanced Processor Build (APB) program.

Transfer of knowledge will also continue to occur within the UNITES end-to-end team members. Transitions to various scientific and applied groups (e.g. NAVOCEANO, TOMS, etc.) are also expected to intensify.

RELATED PROJECTS

This program is closely related to the Harvard 6.1 research "Dynamics of Oceanic Motions" and the 6.2 research "Development of a Regional Coastal and Open Ocean Forecast System". The Multi-Static Active ASW System is currently being transitioned to the Navy through the Advanced Systems Technology Office (ASTO). The predictive probability of detection curves derived from the UNITES Team are being utilized by ASTO in this program.

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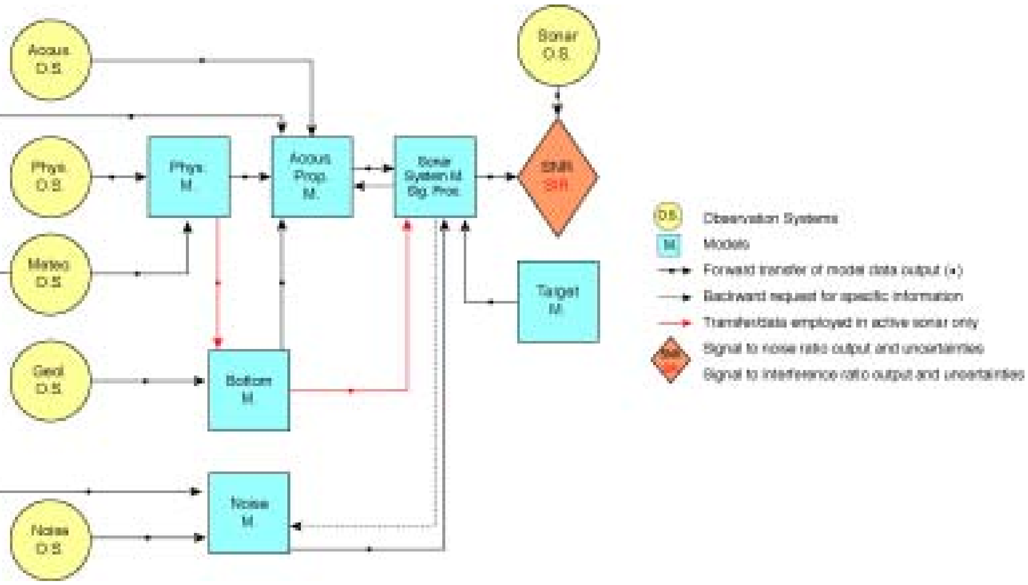

Figure 1. Schematic diagram of the end-to-end system (model point of view)

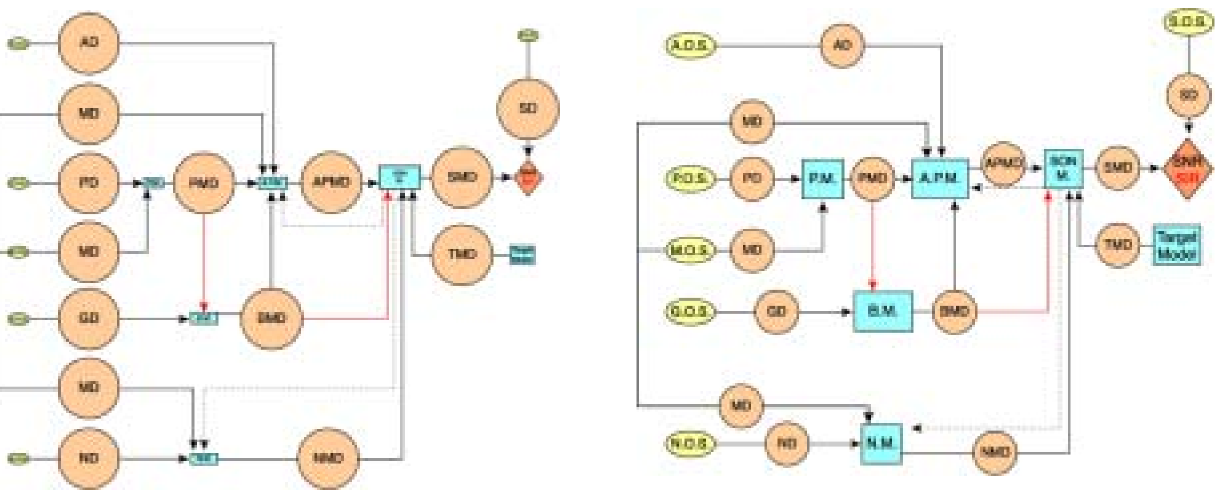

Figure 2. a) As Fig. 1 but from the data point of view;
b) as Fig. 1 but with all (data + model) details.

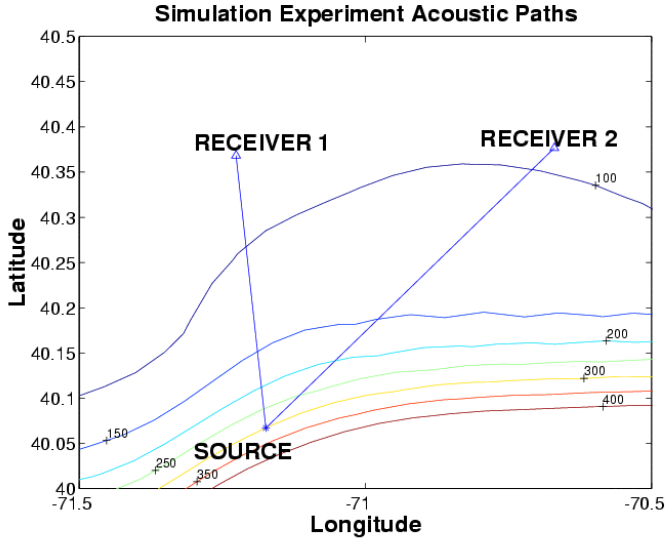

Figure 3. Acoustic paths considered, (as in Shelfbreak-PRIMER), overlaid on bathymetry.

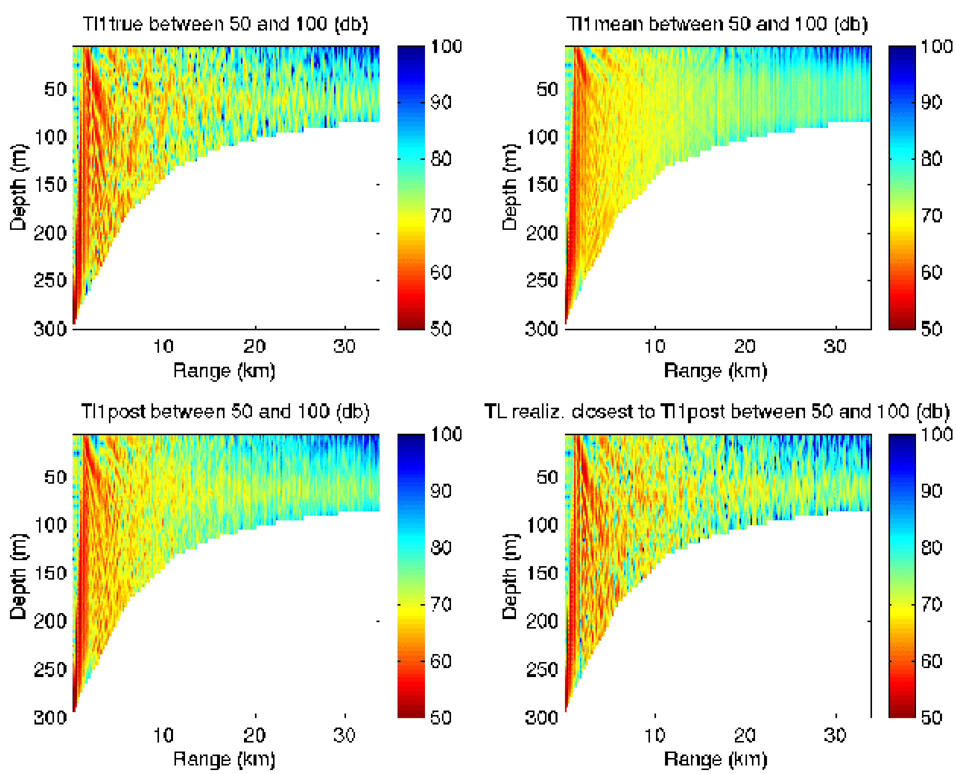

Figure 4. "True" TL, a priori TL, a posteriori TL and TL realization closest to a posteriori TL, all along path 1.

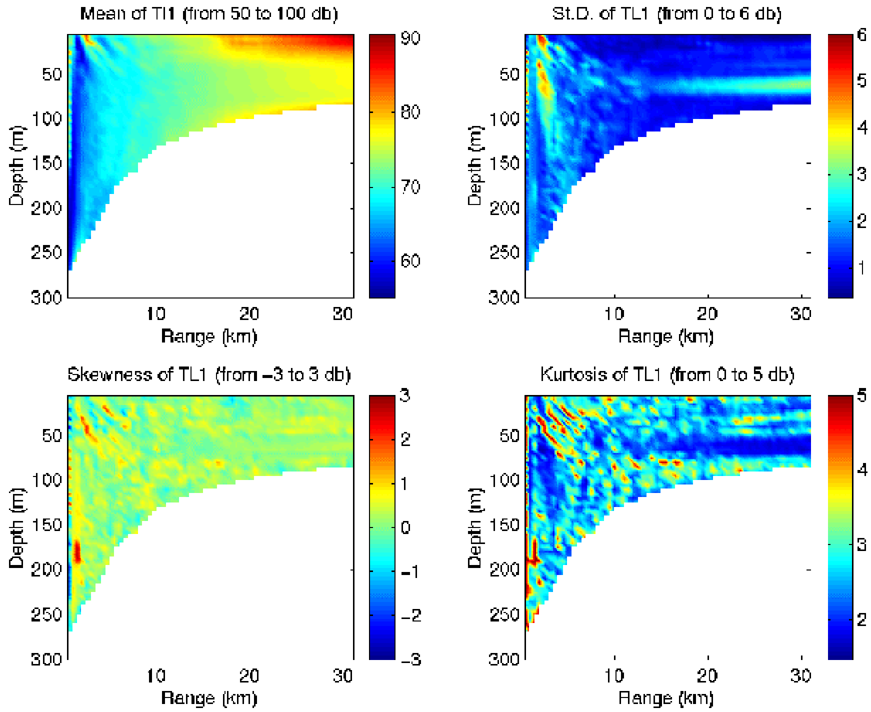

Figure 5. Uncertainty in a broadband TL estimate along PRIMER path 1, as computed and transferred by ESSE, from the environment, through the acoustic and processing, to the sonar equation.

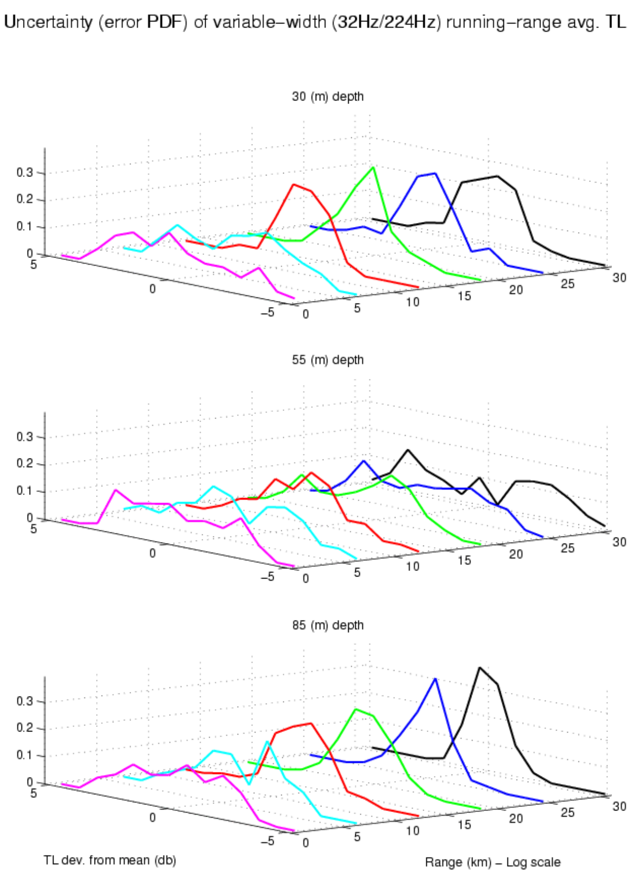

Figure 6. Histograms of deviations from the mean broadband TL (i.e., error PDF estimates) computed by ESSE, as a function of range and depth along PRIMER path 1.